INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

SCF_Lab
INFN LNF

Lunar Laser Ranging test of General Relativity

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For the SCF_Lab Team

http://www.lnf.infn.it/esperimenti/etrusco

Outline

- Introduction
- Test of General Relativity
- 1st vs 2nd Generation of LLR
- Software package
- Data analysis

General Relativity

Einstein’s general theory of relativity (GR) 1915

⬇

Anomalous perihelion precession of Mercury’s orbit

Eddington’s 1919 observations of star lines of sight during a solar eclipse confirmed the doubling of the deflection angles predicted by GR

Following these beginnings, GR has been verified at higher accuracy.

Tests of General Relativity

- Measurement of relativistic geodetic precession of lunar orbit, a true three-body effect (3 m ± 1.9 cm)/orbit

- Violation of Weak and Strong Equivalence Principle (WEP/SEP)

- Through SEP: Parametrized Post-Newtonian (PPN) parameter β, measures the non-linearity of gravity

- Time variation of universal gravitational constant G

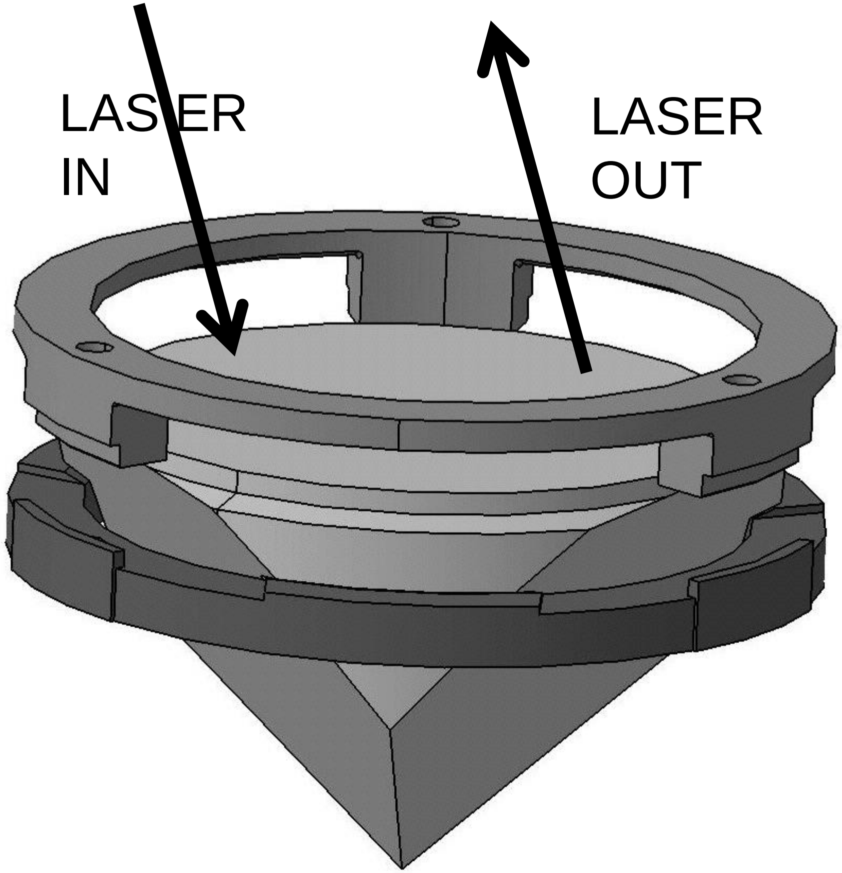
- Tests of inverse square law ($1/r^2$)

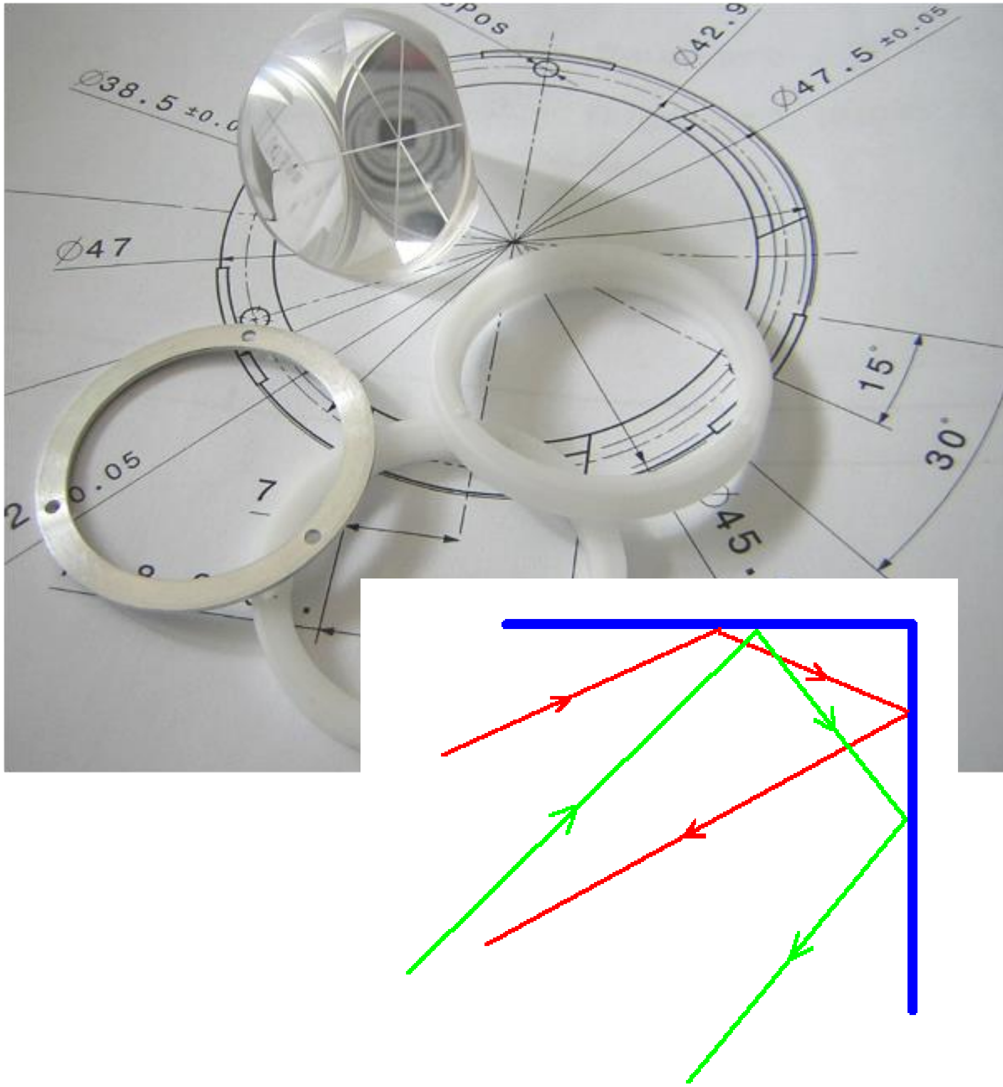
LLR tests of General Relativity

* J. G. Williams, S. G. Turyshev,and D. H. Boggs, PRL 93, 261101 (2004)

Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	Single Reflectors	
			1 mm	0.1 mm
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}\mathrm{yr}^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession		$\lvert k_{gp}\rvert<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

Corner Cube Retroreflector



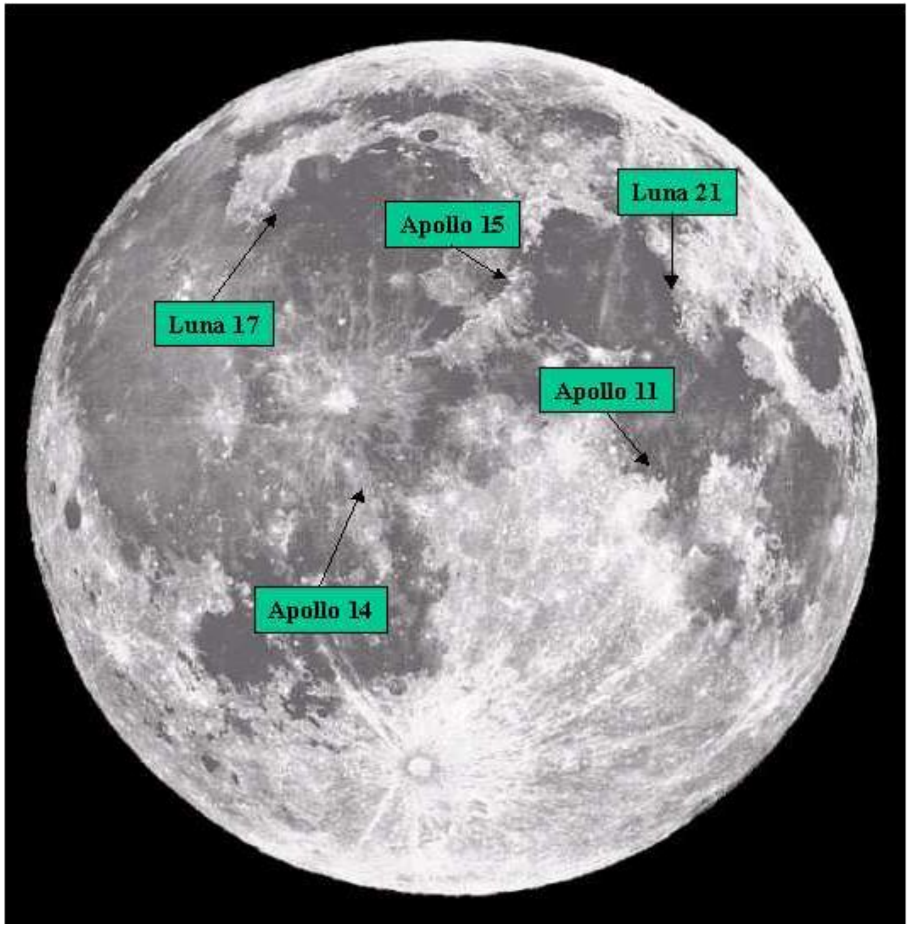


CCRs Arrays on the Moon

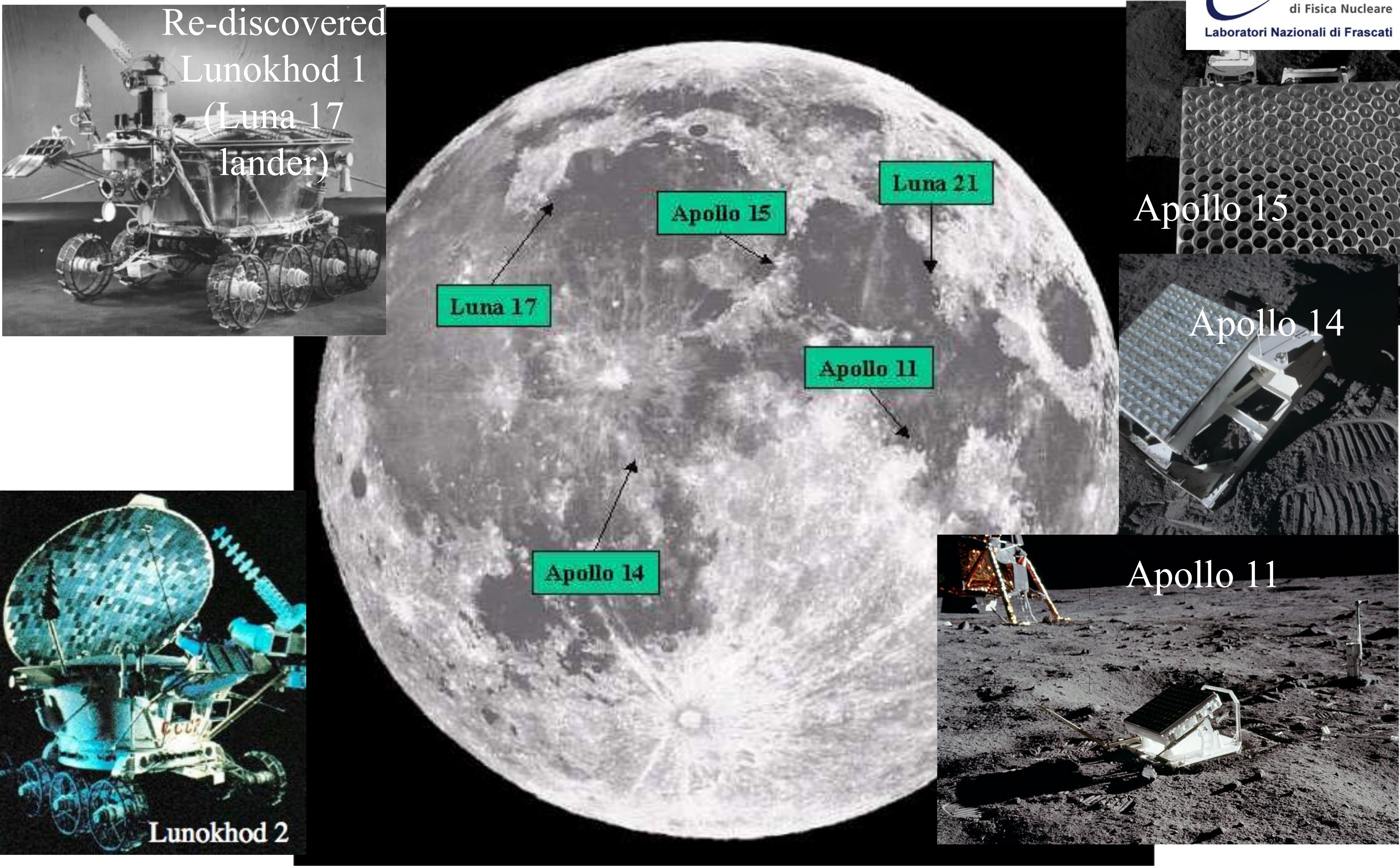
Relative sizes and separation of the Earth–Moon.
An LLR pulse takes 1.255 sec for the mean orbital distance.

Locations of 1st Gen. Lunar Retroreflector Arrays

Retroreflectors deployed by Apollo 11, 14, 15



CCRs Arrays on the Moon



Re-discovered Lunokhod 1 (Luna 17 lander)

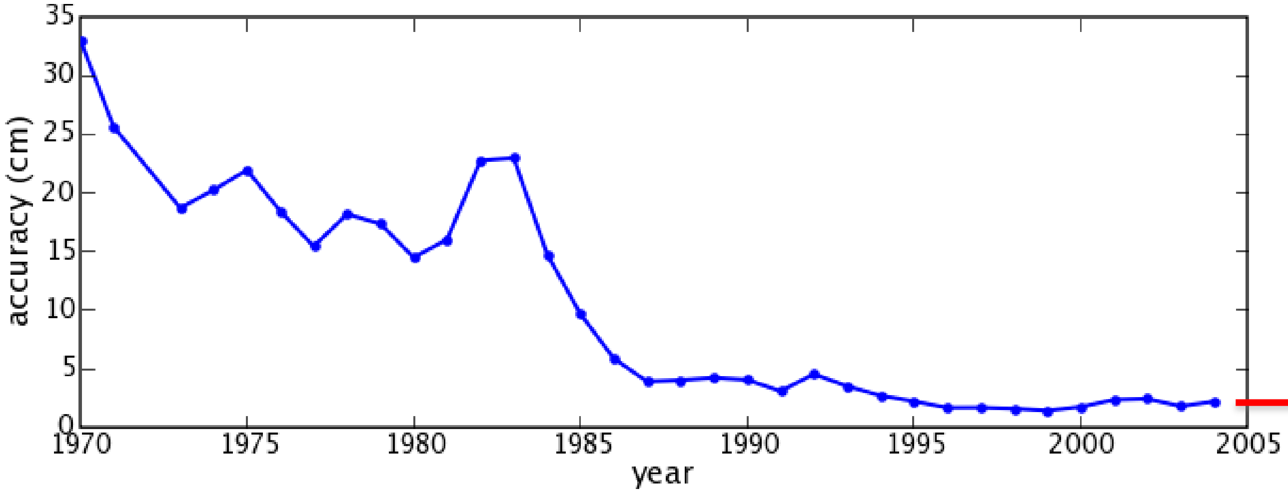
Lunokhod 2

Apollo 15

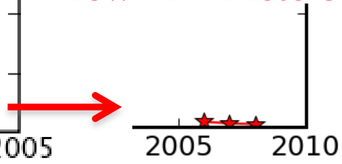
Apollo 14

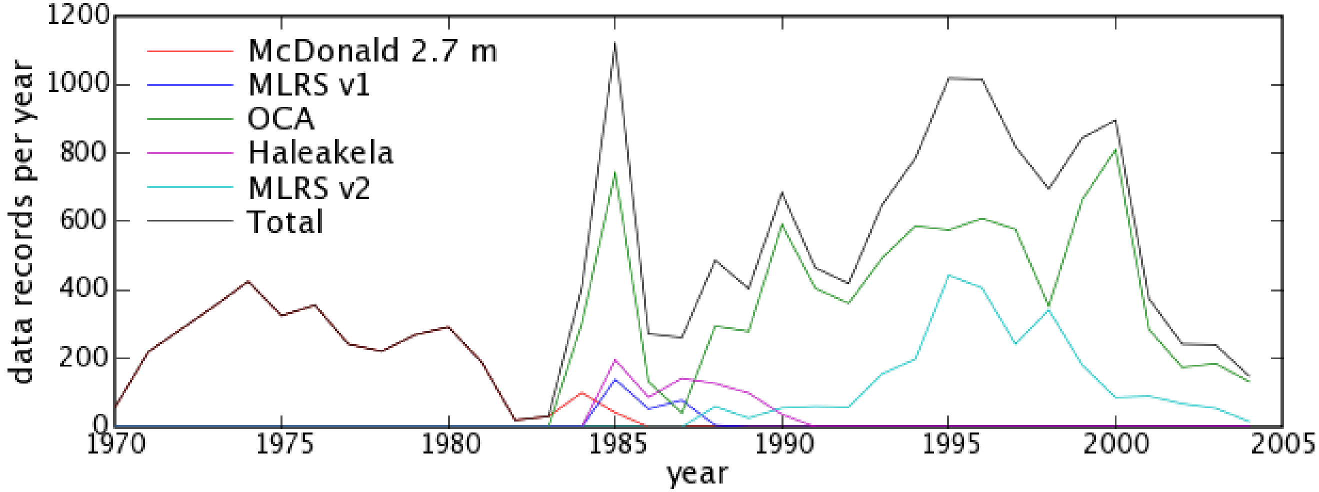
Apollo 11

CCRs Arrays on the Moon

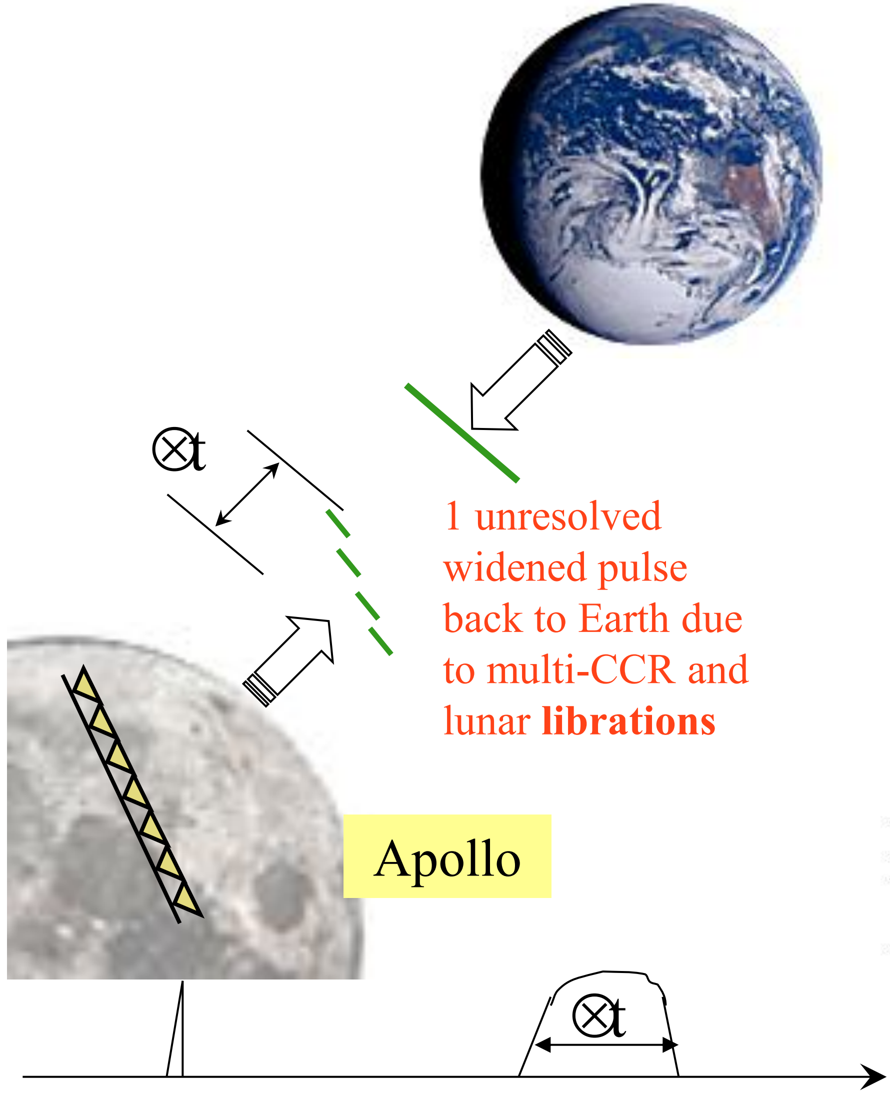


With APOLLO, “Apache Point Observatory Lunar Laser Operation”, In New Mexico: few millimeters





1^{st} Generation LLR

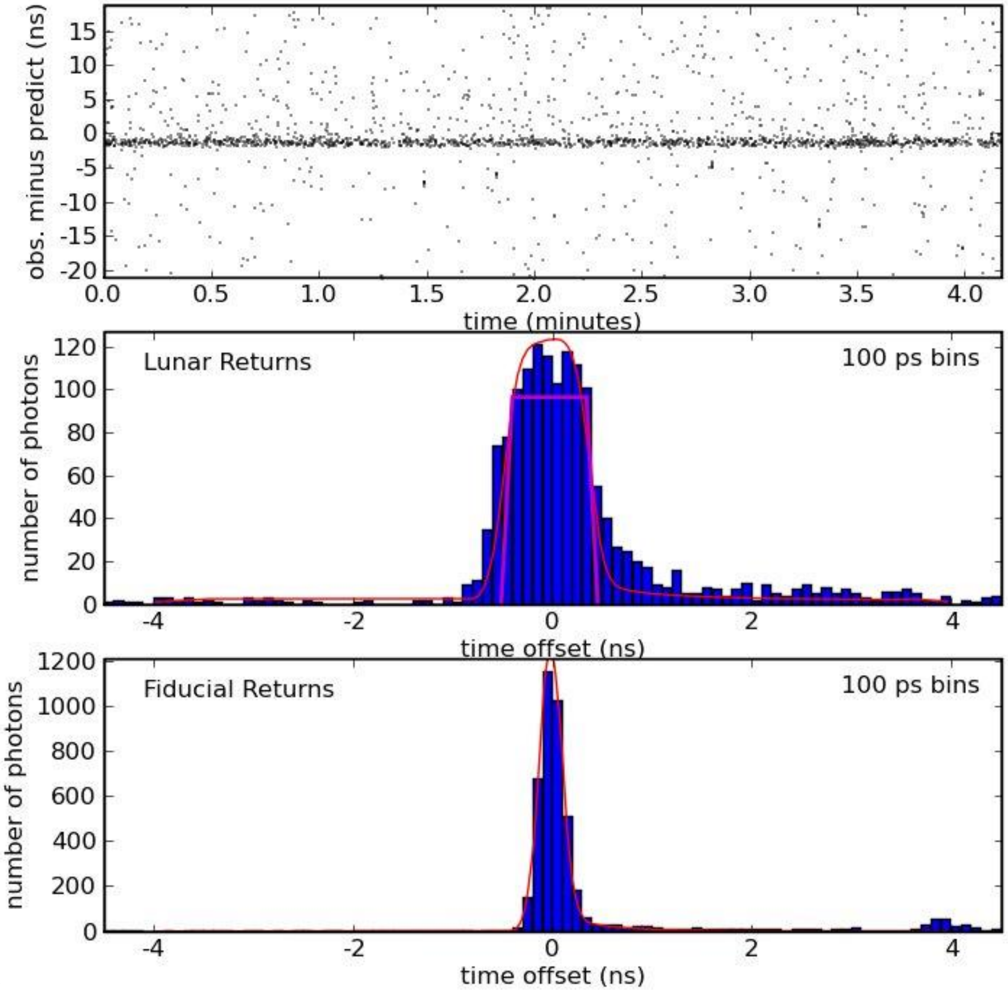


1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**

Apollo

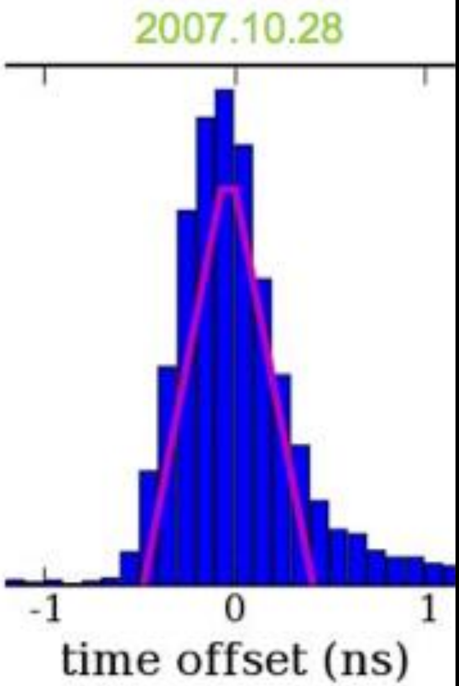
Short Pulse to Moon

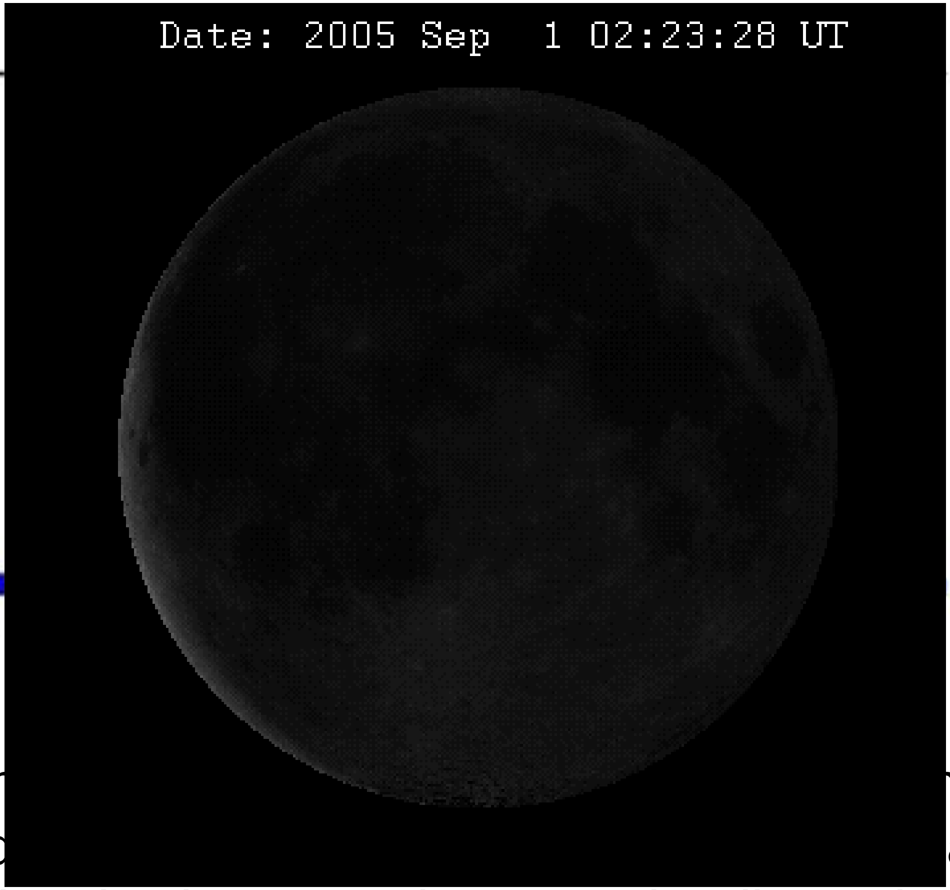
Wide Pulse to Earth

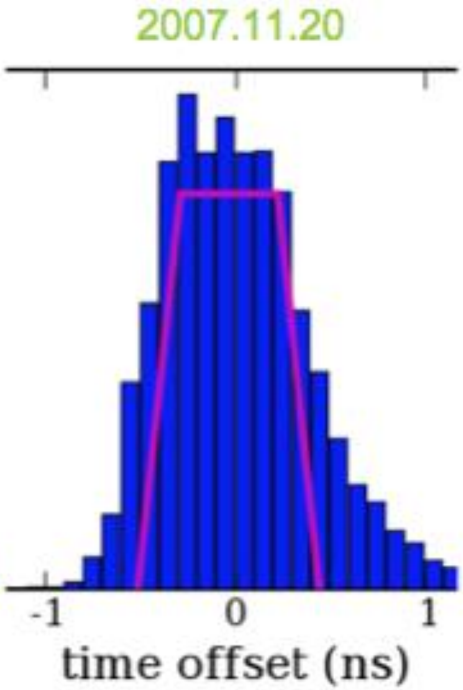


Librations

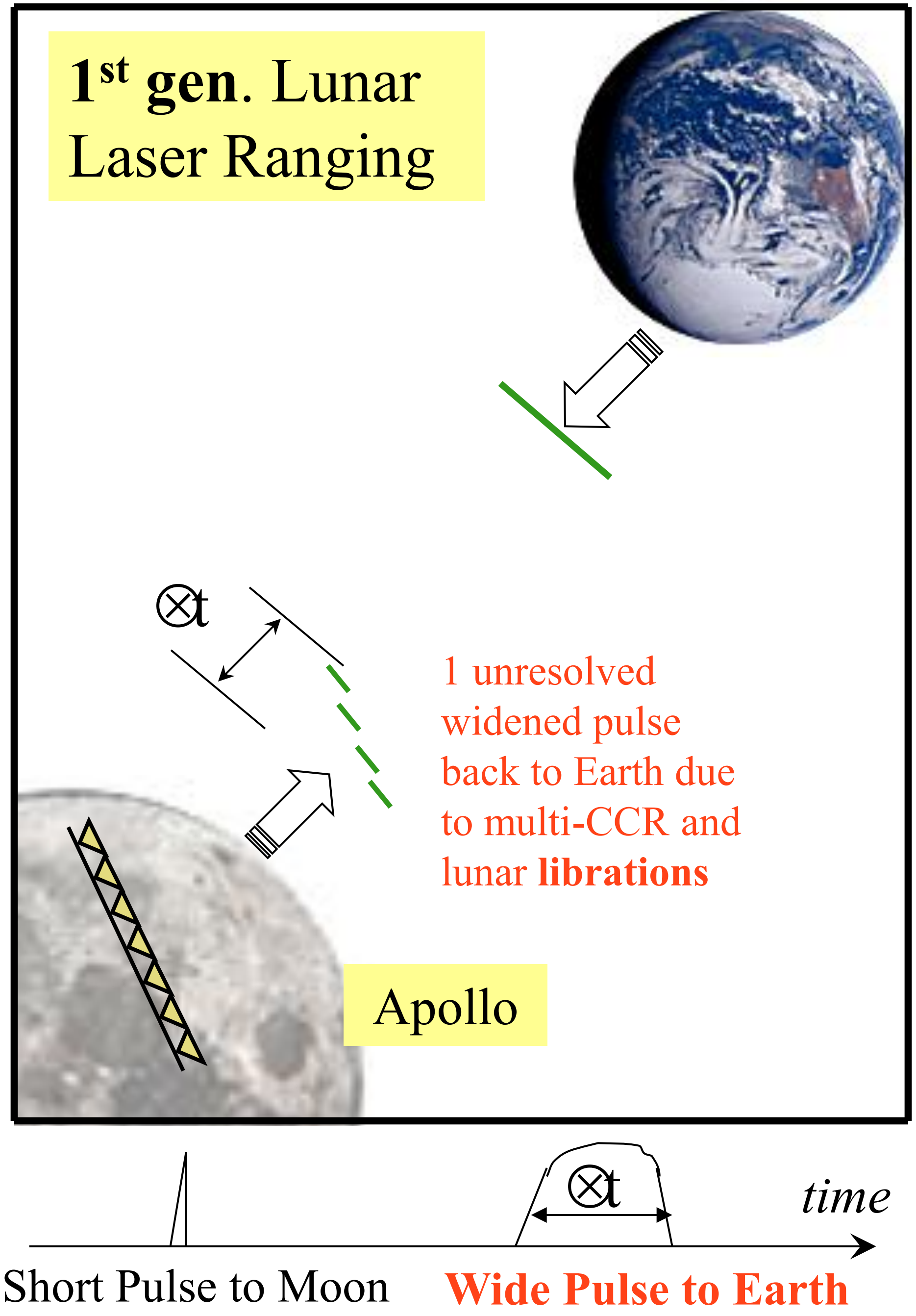
Effect of multi-CCR array orientation due to lunar librations







Due to this phenon hat one corner of the array is more c al centimeters. Because the libration tilt, the arrays increase the dimension of the LLR pulse coming back to the Earth.



1^{st} **gen**. Lunar Laser Ranging

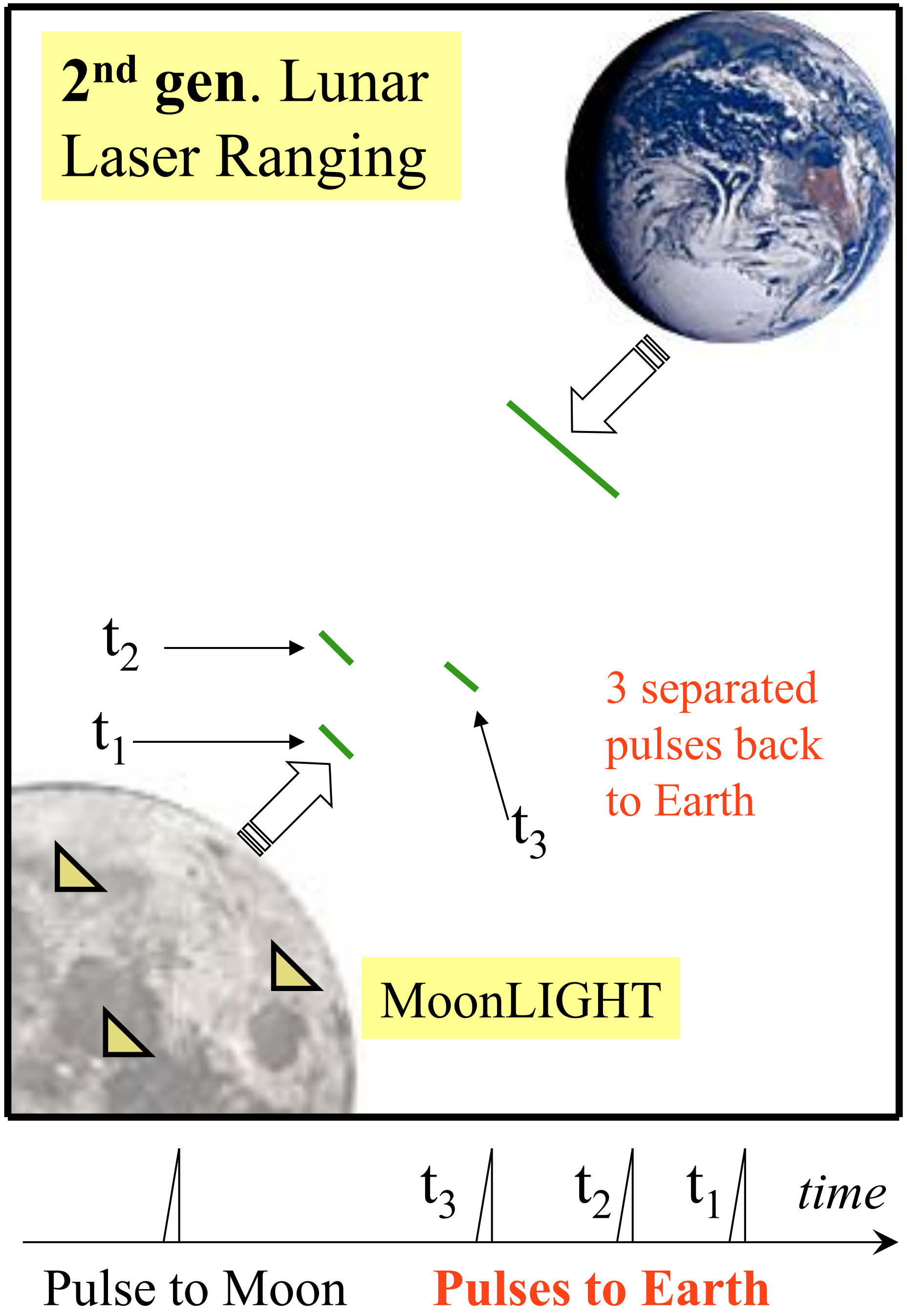
$\otimes t$

1 unresolved widened pulse back to Earth due to multi-CCR and lunar **libations**

Apollo

Short Pulse to Moon

Wide Pulse to Earth



2^{nd} **gen**. Lunar Laser Ranging

t_2

t_1

t_3

3 separated pulses back to Earth

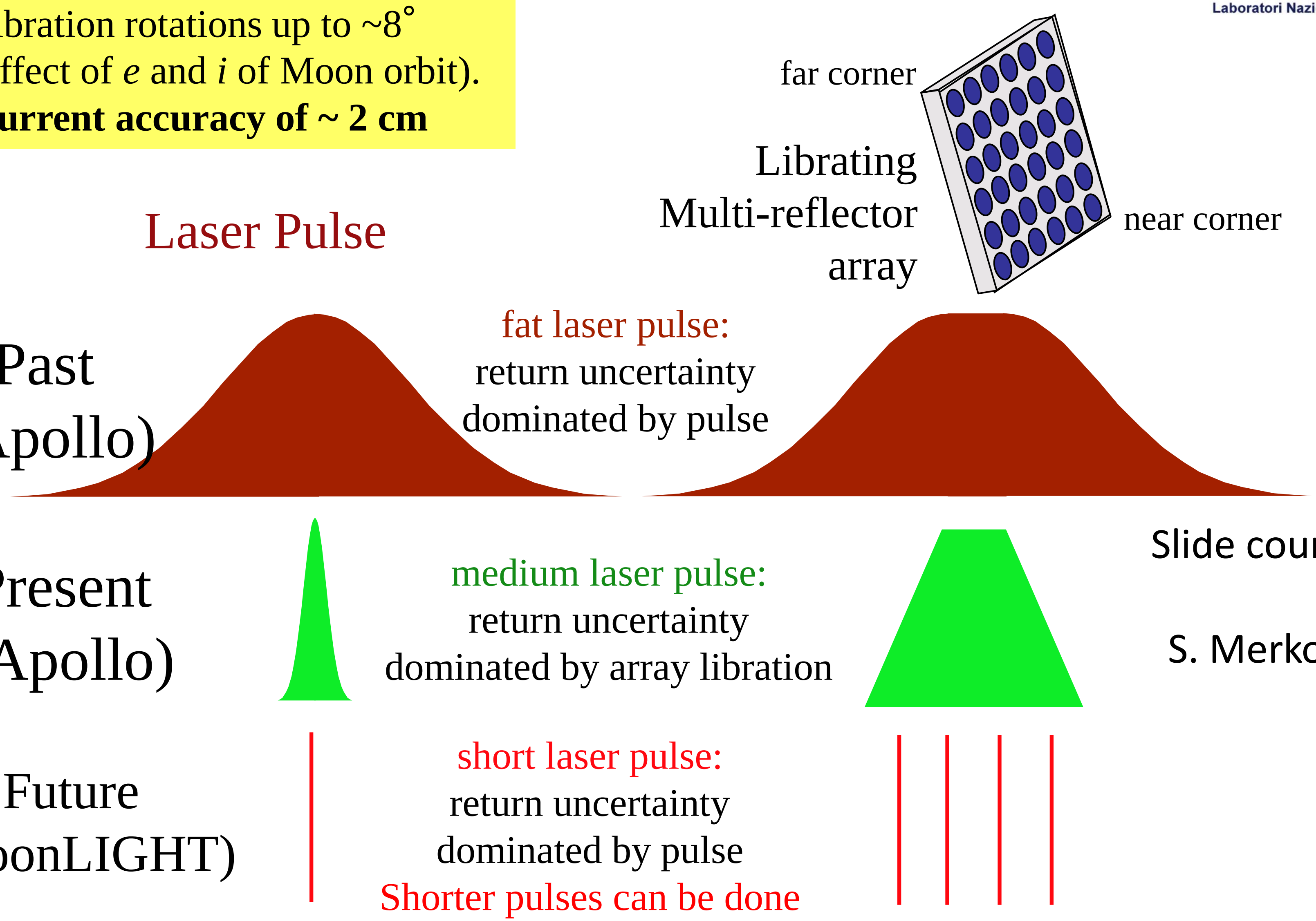
MoonLIGHT

Pulse to Moon

Pulses to Earth

LLRRA21/MoonLIGHT

Libration rotations up to ~8°
(effect of *e* and *i* of Moon orbit).
Current accuracy of ~ 2 cm



Laser Pulse

far corner

Librating Multi-reflector array

near corner

Past (Apollo)

fat laser pulse:
return uncertainty
dominated by pulse

Present (Apollo)

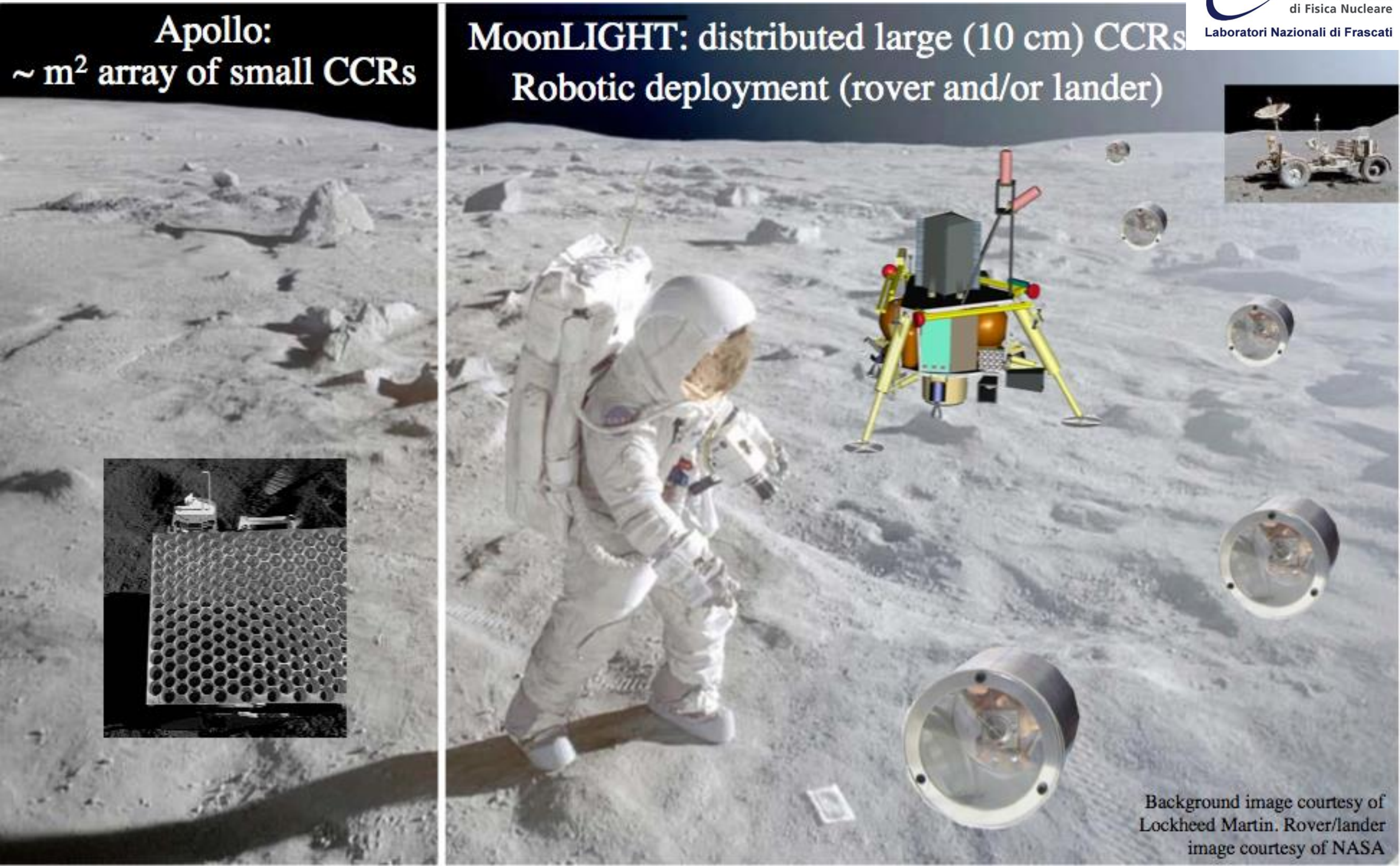
medium laser pulse:
return uncertainty
dominated by array libration

Future (MoonLIGHT)

short laser pulse:
return uncertainty
dominated by pulse
Shorter pulses can be done

Slide courtesy
of
S. Merkowitz

LLRRA21/MoonLIGHT

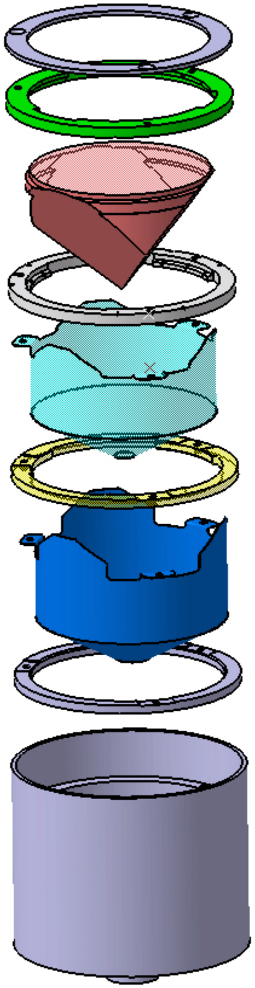


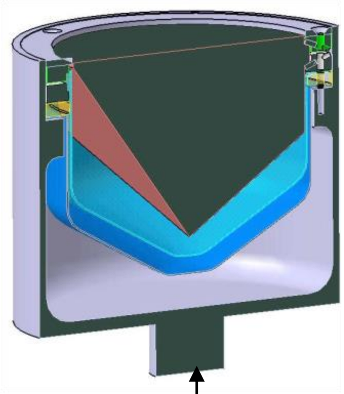
Apollo:
~ m^2 array of small CCRs

MoonLIGHT: distributed large (10 cm) CCRs
Robotic deployment (rover and/or lander)

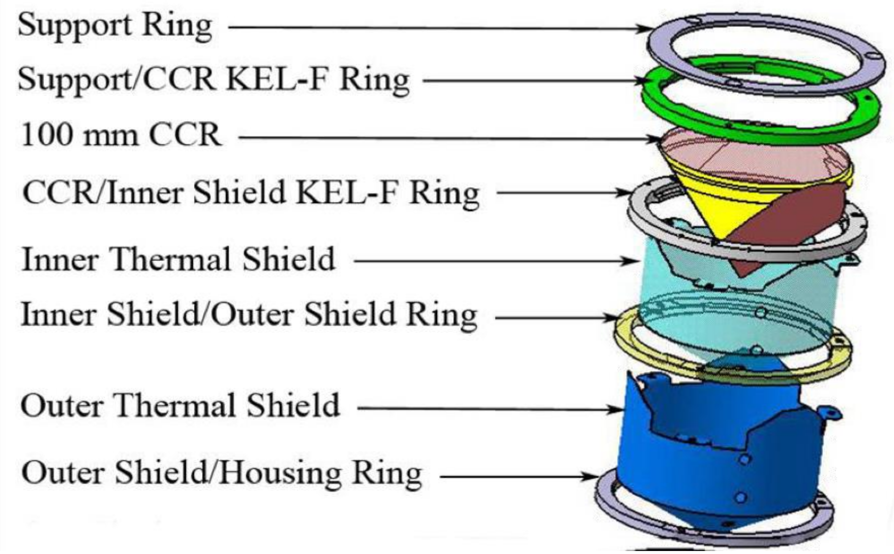
Background image courtesy of Lockheed Martin. Rover/lander image courtesy of NASA

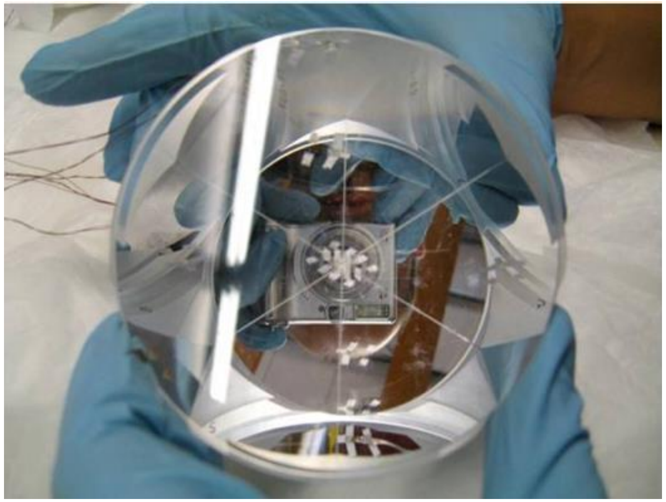
LLRRA21/MoonLIGHT





Threaded hole to deploy P/L on lander, rover, orbiter (or drill bore stem, like used by Apollo astronauts)





Software

Why do we need precise planetary positions?

Two broad requirement categories:

- Defense
- Astronomical need for accurate planetary positions

Besides the intrinsic interest of astronomers in planetary, asteroidal, and cometary positions, knowledge of these positions over time - called an *ephemeris* - fundamentally affects many areas of solar system and even stellar astronomy:

Software

- To the general public, perhaps the most apparent astronomical need for precise planetary positions is in spacecraft navigation.

- Solar system celestial mechanics depends greatly on accurate positions. Theories of planetary and satellite motions live or die according to how well their predictions agree with observational knowledge of positions. These theories are the means by which we develop our most fundamental understanding of the many complicated dynamical processes and interactions in the solar system.

- Another area where accurate knowledge of planetary positions is crucial is stellar occultations.

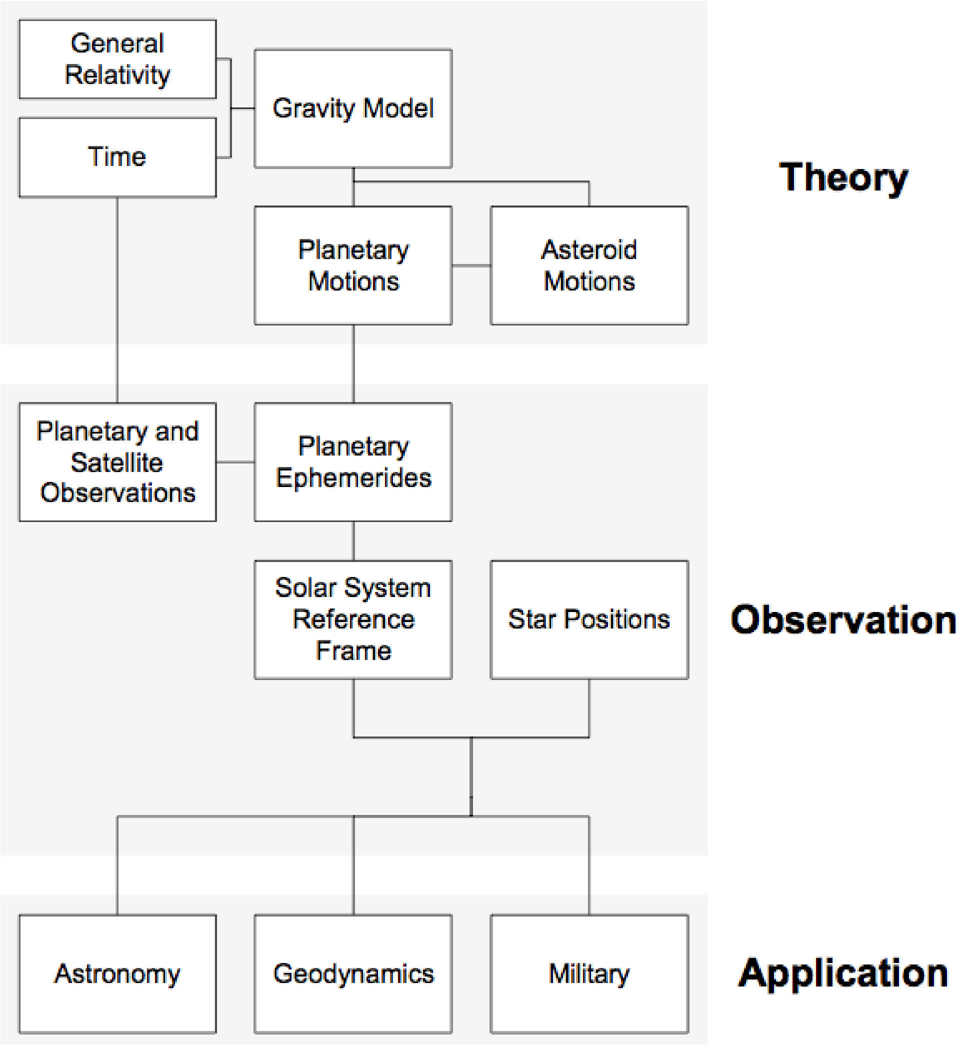
- General Relativity

Dependencies

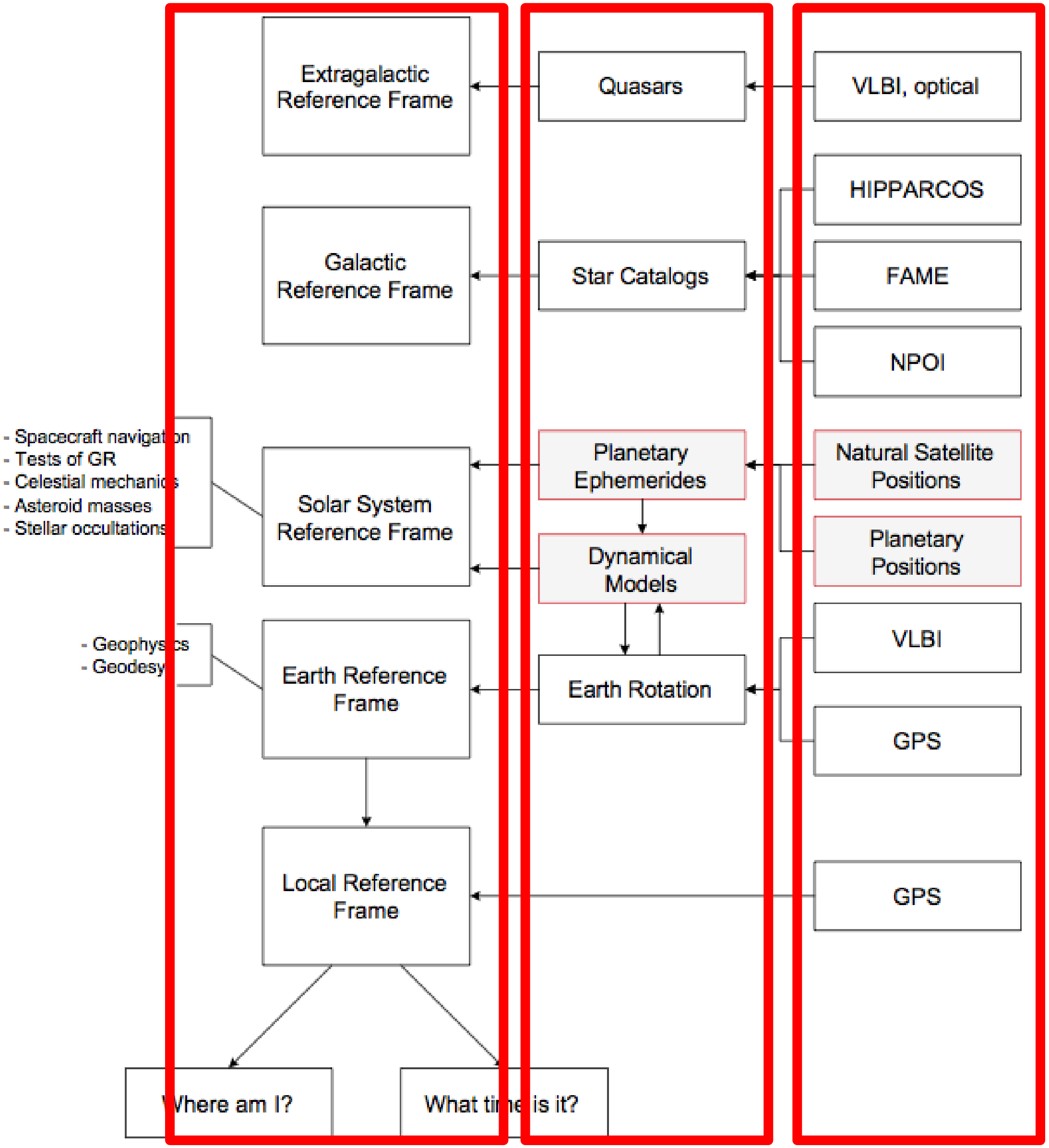
Observations can be interpreted only in the context of our understanding (theoretical models) of the solar system and its dynamics.

Observations can then be used to correct and update our theoretical models.

Combination of planetary system model plus stellar position catalogs, gives rise to a multitude of practical applications



Reference Frame



Hierarchy of frames

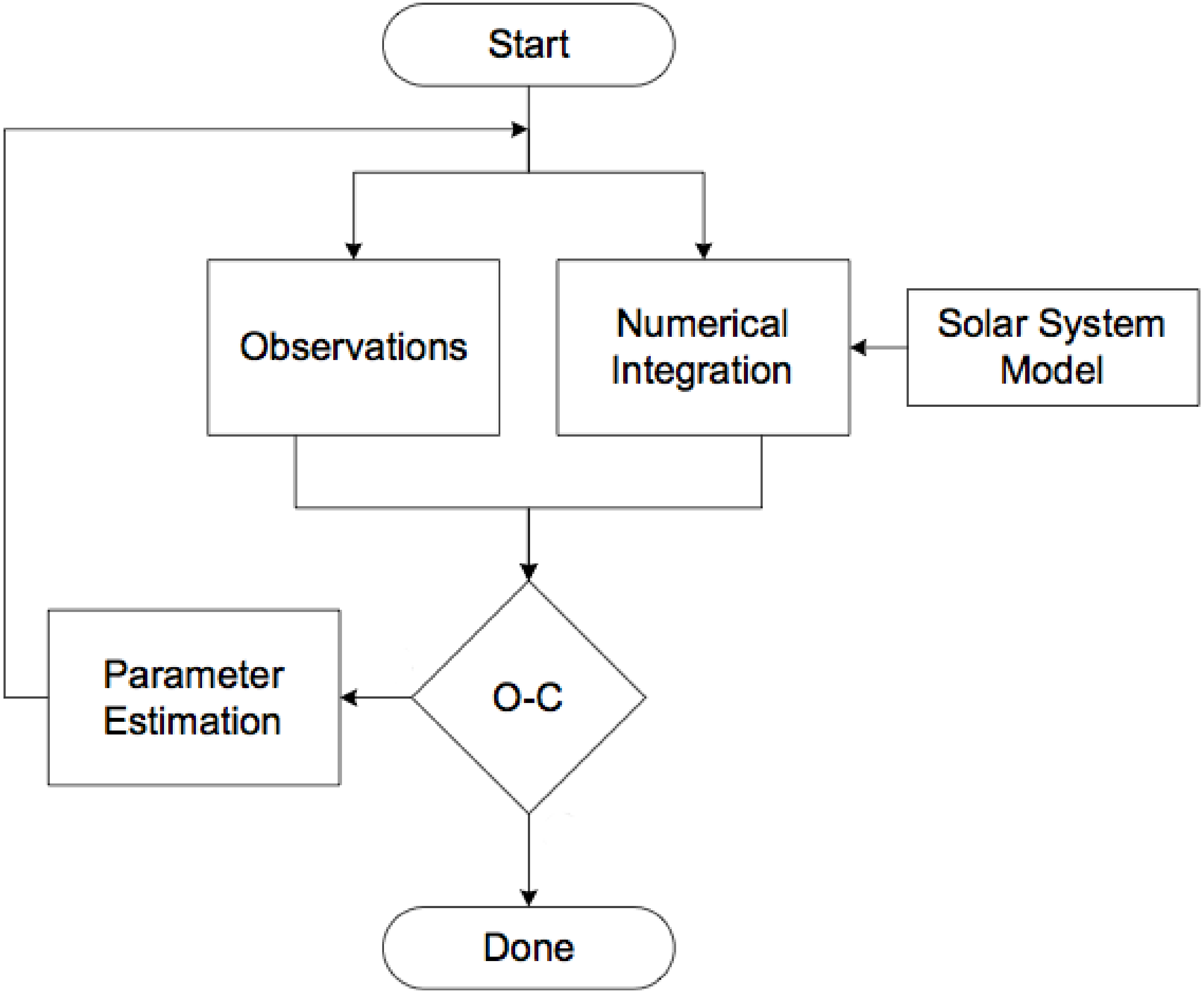
Input category or dynamics type that corresponds to the associated reference frame.

Most important observation types that determine the reference frame.

Generating Predictions

How

- Mu
- De
  e then
  inte
  s
  pla
- Sin
  e
  ava


Start

Observations

Numerical Integration

Solar System Model

O-C

Parameter Estimation

Done

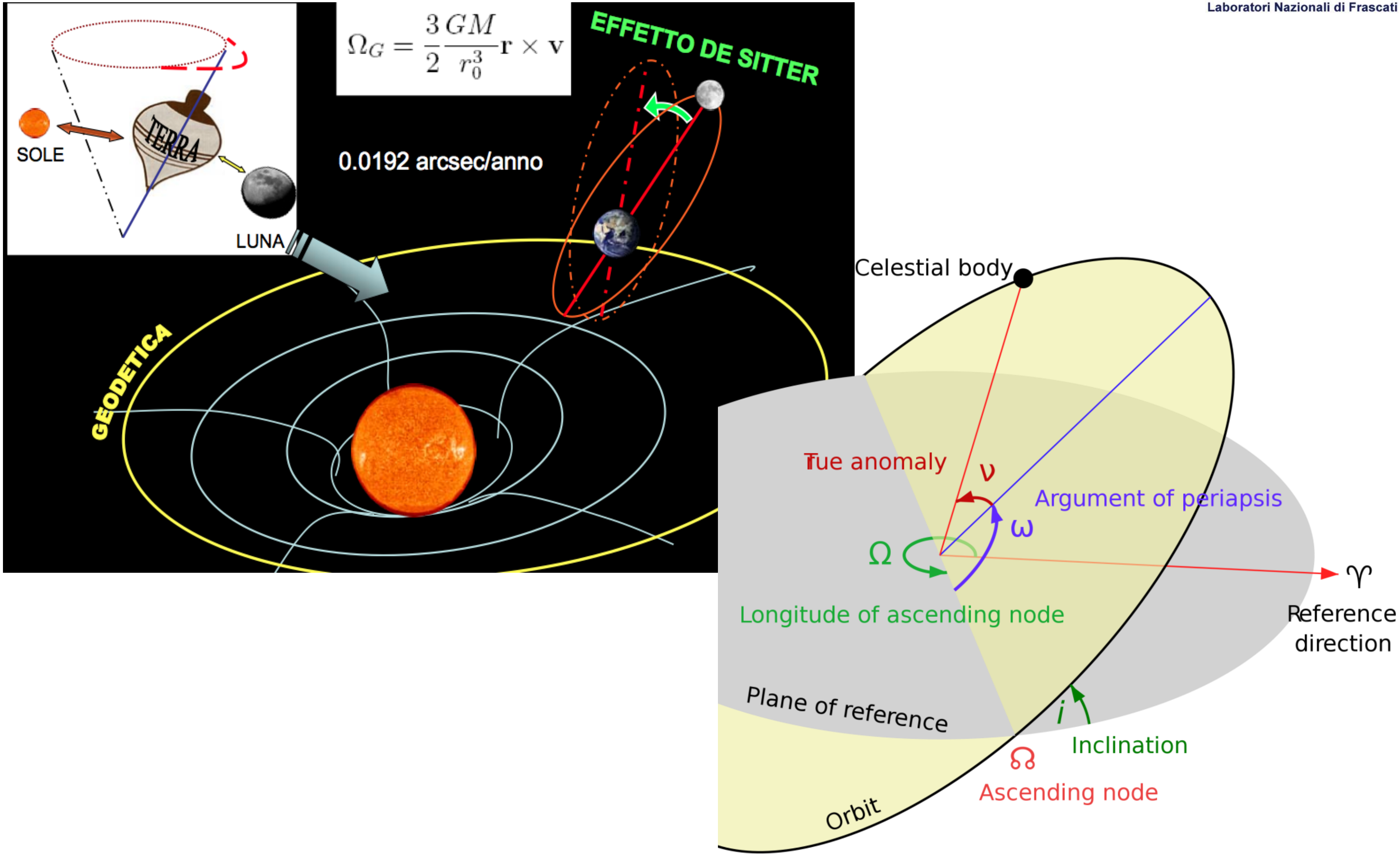
Geodetic Precession

The term geodetic effect has two slightly different meanings as the moving body may be spinning or non-spinning. Non-spinning bodies move in geodesics, whereas spinning bodies move in slightly different orbits.

The difference between de Sitter precession and Lense-Thirring precession is that the de Sitter effect is due simply to the presence of a central mass, whereas Lense-Thirring precession is due to the rotation of the central mass.

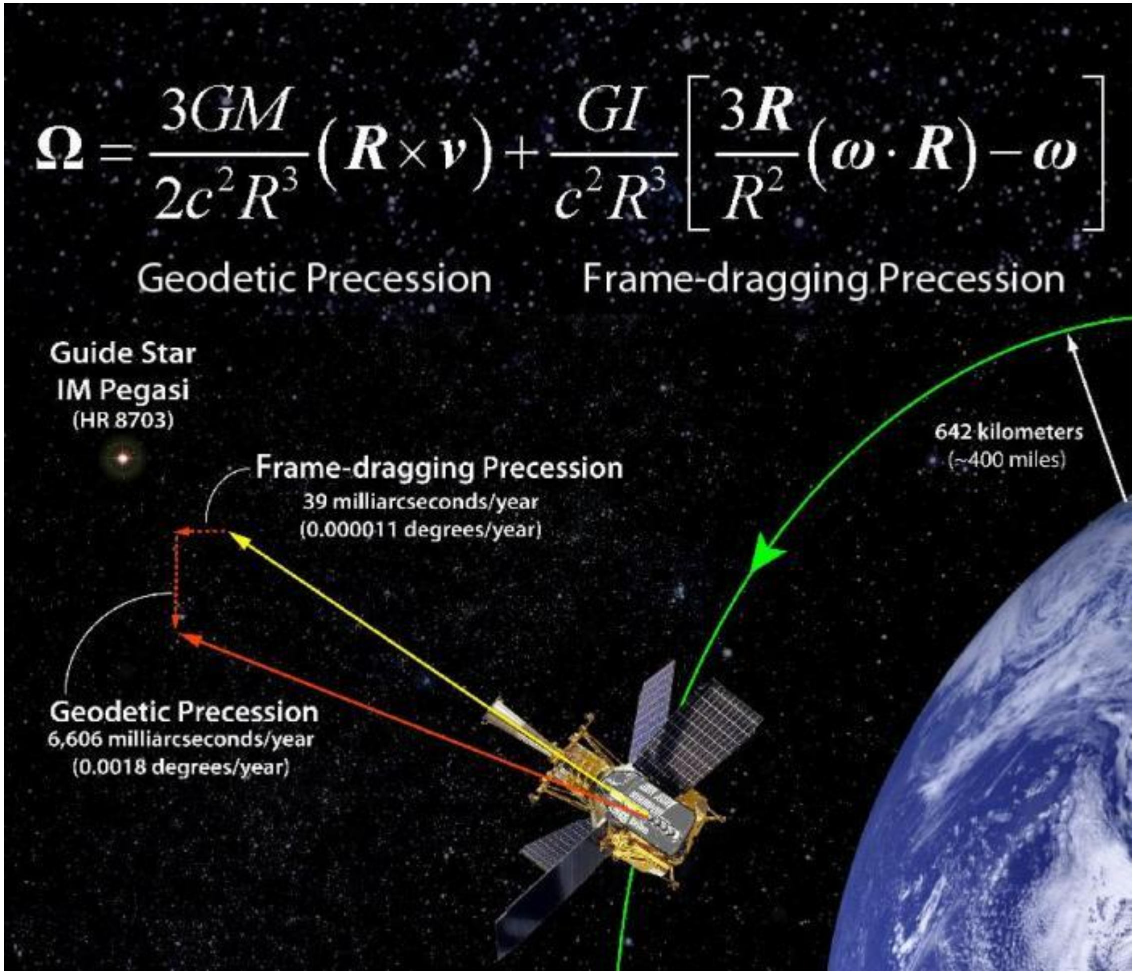
The total precession is calculated by combining the de Sitter precession with the Lense-Thirring precession.

Geodetic Precession


$$\Omega_G = \frac{3}{2}\frac{GM}{r_0^3}\mathbf{r} \times \mathbf{v}$$

0.0192 arcsec/anno

Geodetic Precession



The GR test of the geodetic precession, evaluated with LLR data and expressed as a relative deviation from the value expected in GR, is:

$K_{GP} = -0.0019 \pm 0.0064$

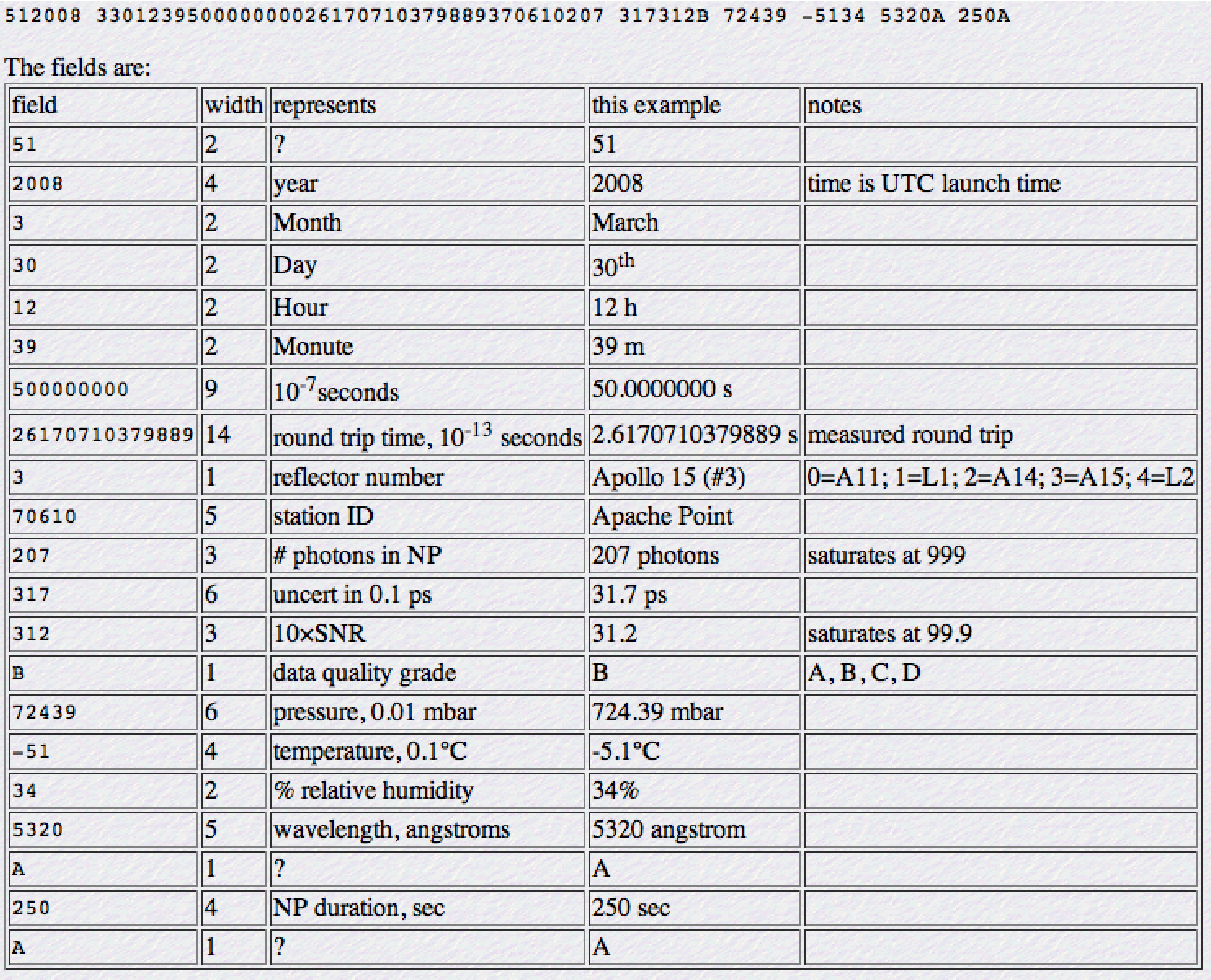
Planetary Ephemeris Program

In order to analyze LLR data we used the PEP software, developed by the CfA, by I. Shapiro et al. starting from 1970s.

The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for ”Computation”), O-C.

”Observed” is round-trip time of flight. ”Computed” is modeled by the PEP software.

APOLLO Normal Point Data



```
512008 330123950000000026170710379889370610207 317312B 72439 -5134 5320A 250A
```

The fields are:

field	width	represents	this example	notes
51	2	?	51	
2008	4	year	2008	time is UTC launch time
3	2	Month	March	
30	2	Day	30th	
12	2	Hour	12 h	
39	2	Monute	39 m	
500000000	9	10^{-7} seconds	50.0000000 s	
26170710379889	14	round trip time, 10^{-13} seconds	2.6170710379889 s	measured round trip
3	1	reflector number	Apollo 15 (#3)	0=A11; 1=L1; 2=A14; 3=A15; 4=L2
70610	5	station ID	Apache Point	
207	3	# photons in NP	207 photons	saturates at 999
317	6	uncert in 0.1 ps	31.7 ps	
312	3	10×SNR	31.2	saturates at 99.9
B	1	data quality grade	B	A, B, C, D
72439	6	pressure, 0.01 mbar	724.39 mbar	
-51	4	temperature, 0.1°C	-5.1°C	
34	2	% relative humidity	34%	
5320	5	wavelength, angstroms	5320 angstrom	
A	1	?	A	
250	4	NP duration, sec	250 sec	
A	1	?	A	

A normal point contains several information e.g. date of observation, atmospheric conditions, as well as time of flight, data quality and CCR arrays

We convert this in “PEP formalism” with an internal subroutine

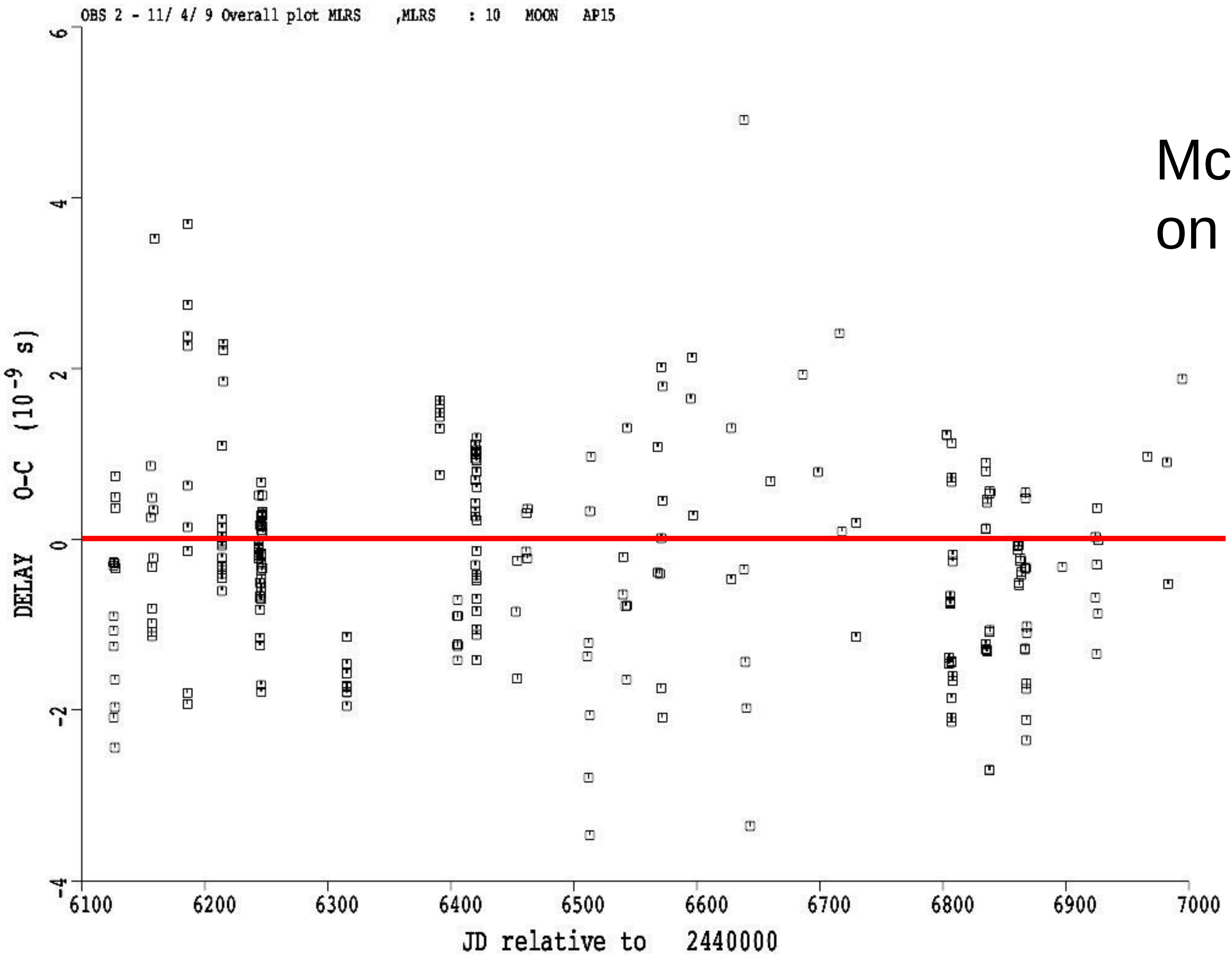
Planetary Ephemeris Program

Two different way to proceed:

- “old stations” (McDonald, Grasse, MLR2)

- Apache Point station

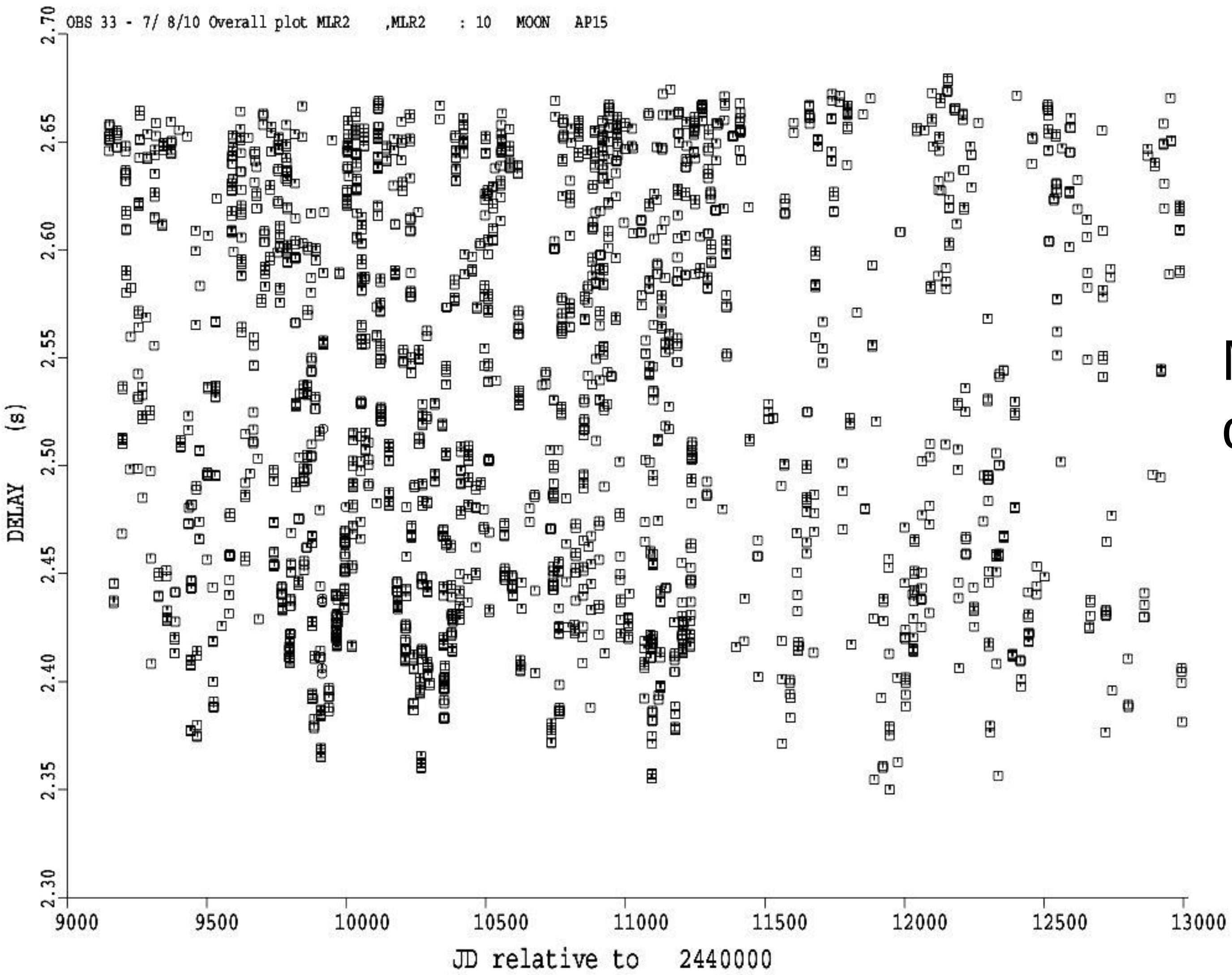
O-C residual analysis with PEP



McDonald station
on Apollo 15 array

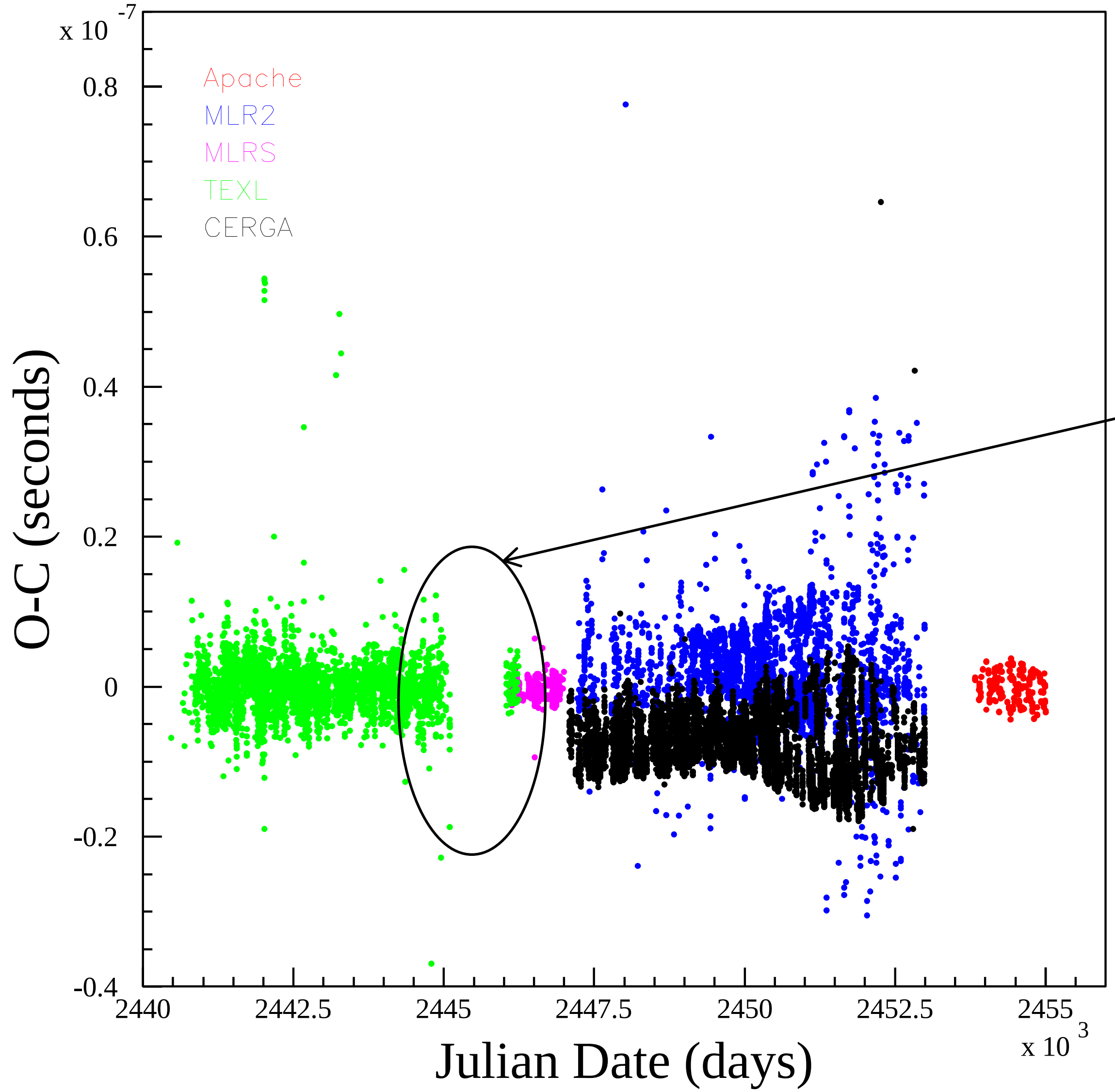
JD is the interval of time in days and fractions of a day since January 1, 4713 BC Greenwich noon.

O-C residual analysis with PEP



McDonald station on Apollo 15 array

O-C residual analysis with PEP



Station maintenance

Manuele Martini

Determination of K_{GP}

K_{GP} is the relative deviation from the value of geodetic precession expected in GR

All together old stations:

$$K_{GP} = (9 \pm 9) \times 10^{-3}$$

Apache Point station:

$$K_{GP} = (-9.6 \pm 9.6) \times 10^{-3}$$

In this analysis $\beta=\gamma=1$, $dG/dt=0$. Nominal errors returned by the fit are significantly smaller than the above estimated values of K_{GP}.

Determination of K_{GP}

Parameter	GR initial value	Final value
K_{GP} CERGA	0	-0.0162

Parameter	GR initial value	Final value
K_{GP} MAUI	0	0.0060

Parameter	GR initial value	Final value
K_{GP} MLR2	0	0.0095

Parameter	GR initial value	Final value
K_{GP} TEXL	0	-0.0441

Determination of K_{GP}

This preliminary measurement must be compared with the best result published by JPL obtained using a completely different software package

$$K_{GP} = (-1.9 \pm 6.4) \times 10^{-3}$$

On the contrary, after the original 2% K_{GP} measurement by CfA in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

Goal: accuracy on K_{GP} of few ‰ with current LLR data

≥ x10 improvement possible only with MoonLIGHTs

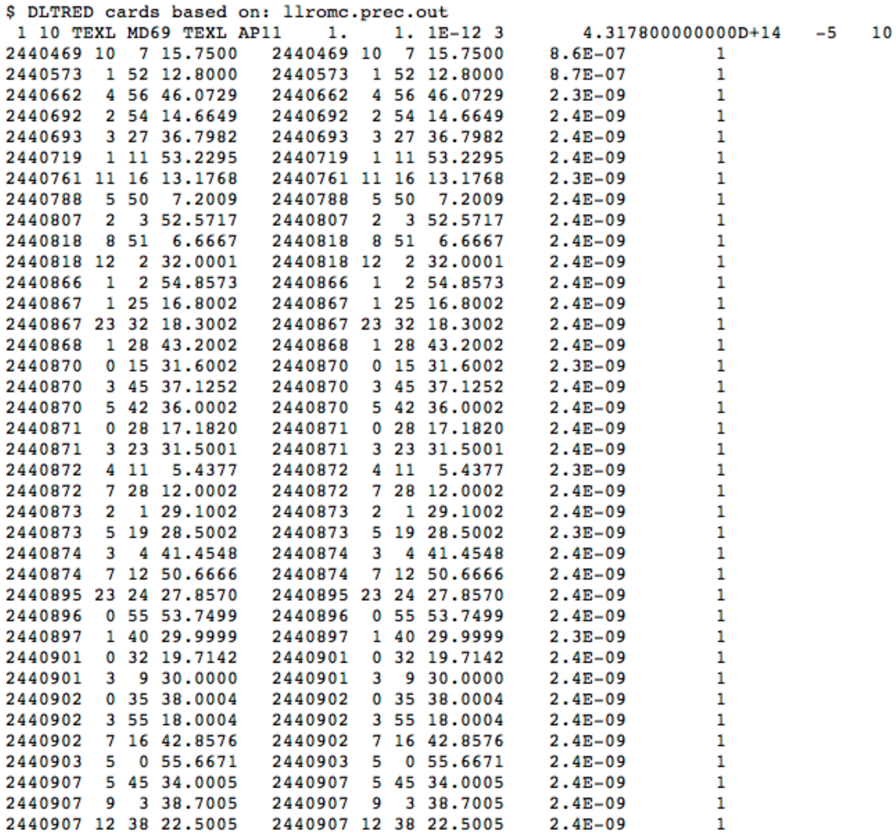
PEP simulation of physics reach of MoonLIGHTs at lunar poles/limbs/equator and on lander/rover/regolith/drill

Dummy observations

PEP can make simulated “dummy” observations.

We are trying to simulate new arrays on lunar surface.

We are trying to simulate arrays at the pole of the Moon and we want to see how the PPN parameters change.



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2440573  1 52 12.8000   2440573  1 52 12.8000    8.7E-07         1
2440662  4 56 46.0729   2440662  4 56 46.0729    2.3E-09         1
2440692  2 54 14.6649   2440692  2 54 14.6649    2.4E-09         1
2440693  3 27 36.7982   2440693  3 27 36.7982    2.4E-09         1
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2440818  8 51  6.6667   2440818  8 51  6.6667    2.4E-09         1
2440818 12  2 32.0001   2440818 12  2 32.0001    2.4E-09         1
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2440868  1 28 43.2002   2440868  1 28 43.2002    2.4E-09         1
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2440871  3 23 31.5001   2440871  3 23 31.5001    2.4E-09         1
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2440872  7 28 12.0002   2440872  7 28 12.0002    2.4E-09         1
2440873  2  1 29.1002   2440873  2  1 29.1002    2.4E-09         1
2440873  5 19 28.5002   2440873  5 19 28.5002    2.3E-09         1
2440874  3  4 41.4548   2440874  3  4 41.4548    2.4E-09         1
2440874  7 12 50.6666   2440874  7 12 50.6666    2.4E-09         1
2440895 23 24 27.8570   2440895 23 24 27.8570    2.4E-09         1
2440896  0 55 53.7499   2440896  0 55 53.7499    2.4E-09         1
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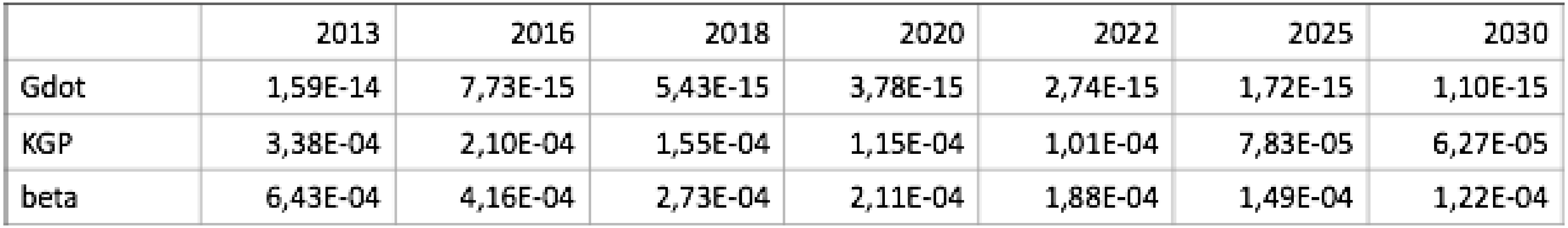
Dummy observations



	2013	2016	2018	2020	2022	2025	2030
Gdot	1,59E-14	7,73E-15	5,43E-15	3,78E-15	2,74E-15	1,72E-15	1,10E-15
KGP	3,38E-04	2,10E-04	1,55E-04	1,15E-04	1,01E-04	7,83E-05	6,27E-05
beta	6,43E-04	4,16E-04	2,73E-04	2,11E-04	1,88E-04	1,49E-04	1,22E-04

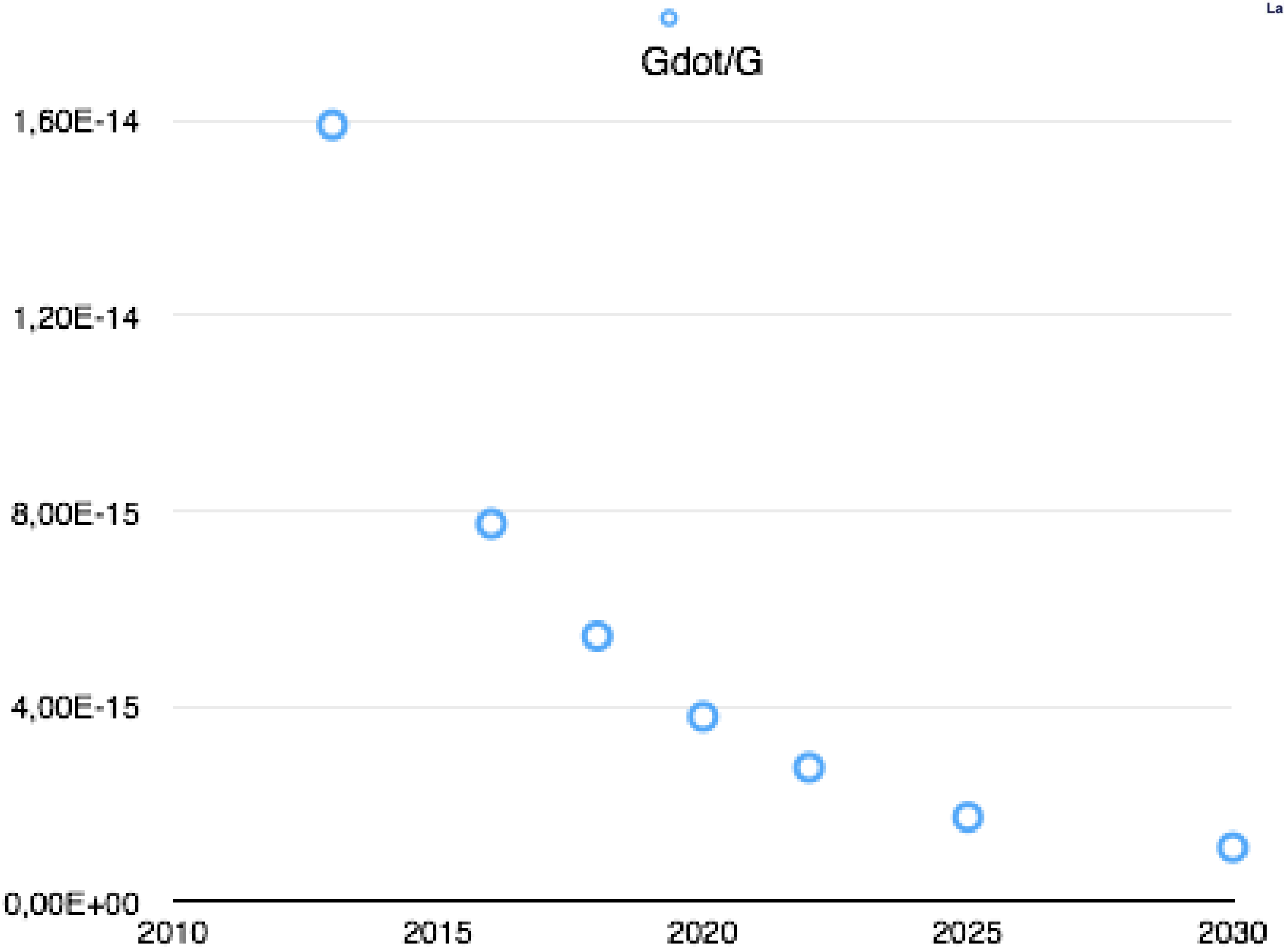
ARRAYS:

AP11-AP14-AP15
Moon Express 65N 40W
Astrobotic 50S 35E
Israel 45N 27.2E

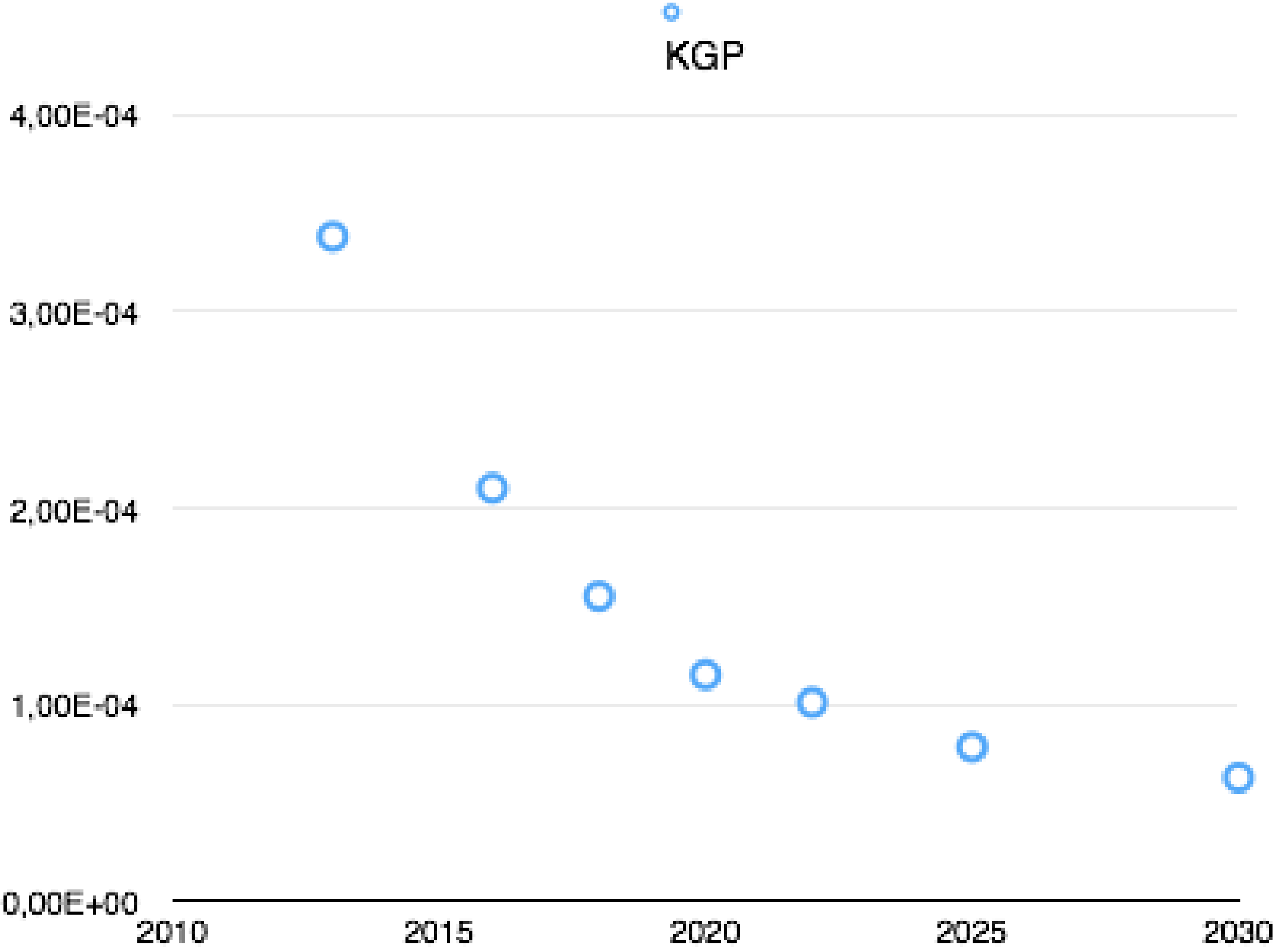
STATIONS:

APOLLO
CERGA
MLRS
MLRO

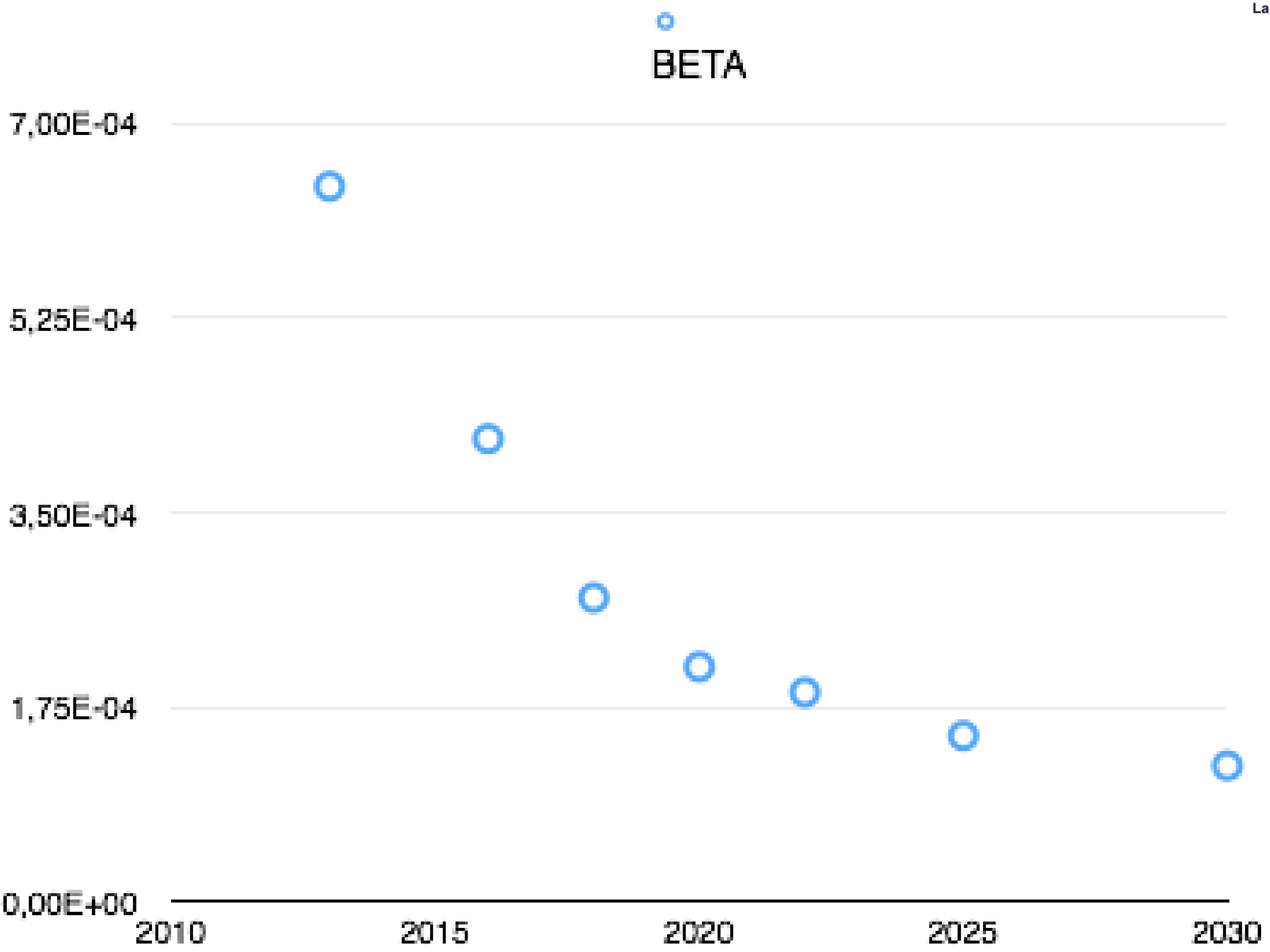
Dummy observations



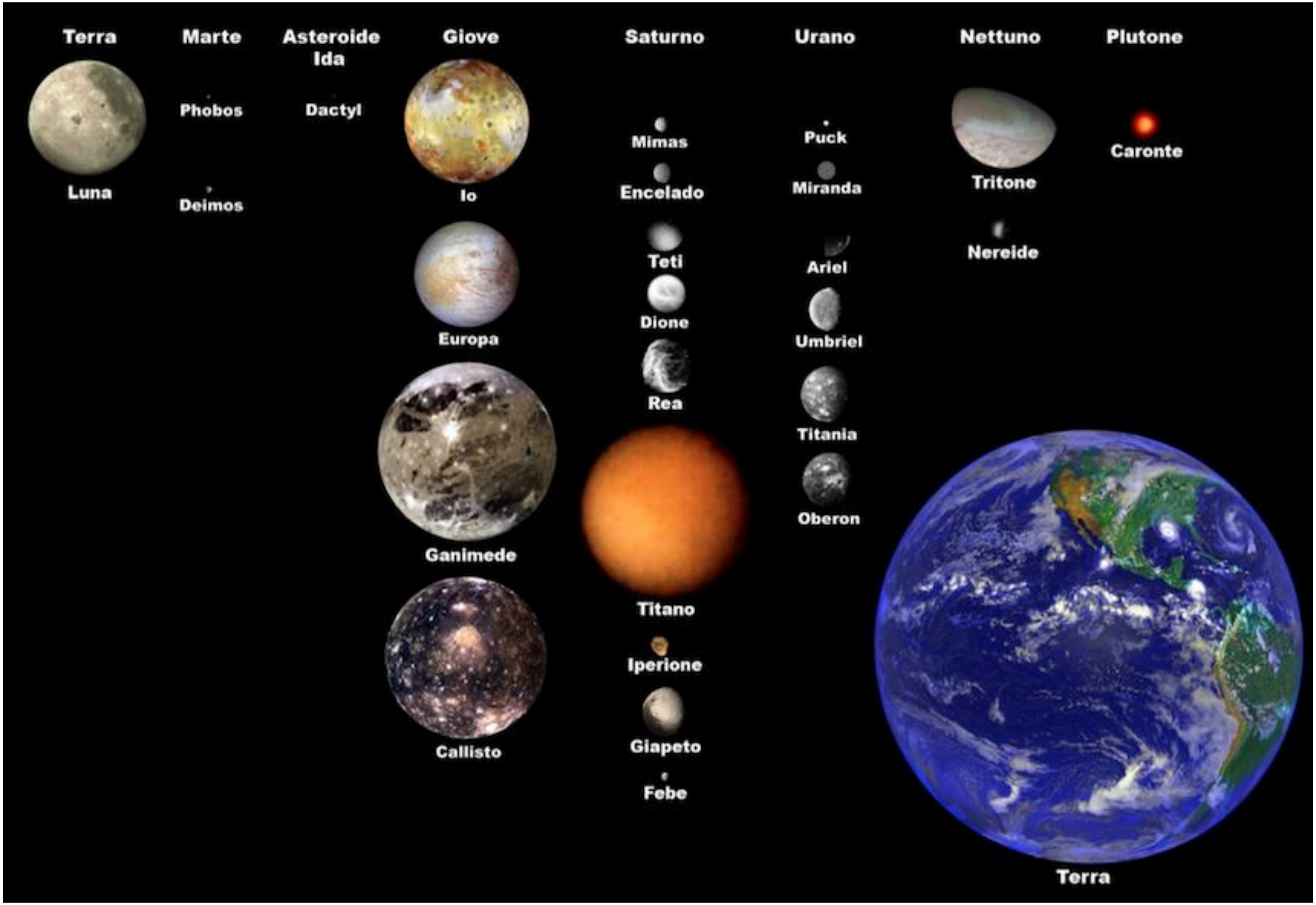
Dummy observations



Dummy observations



Future prospects



Future prospects

- Deepen our knowledge about data and software in order to better estimate the K_{GP} uncertainty and other GR parameters.

- Improve the precision of these kind of measurements ranging not only to the Moon, but also to satellites around the Earth and primarily to LAGEOS, thus improving station intercalibration.

- We have the option to implement the equations of motion of space-time torsion gravity inside PEP and study not only the secular variation of geodetic precession , but also periodic signatures of torsion on the geodetic precession and on other PPN parameters

THANK YOU FOR YOUR ATTENTION

ANY COMMENTS/QUESTIONS?